A national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy

National Renewable Energy Laboratory
Innovation for Our Energy Future

Analysis of Fuel Cell Vehicle Hybridization and Implications for Energy Storage Devices

4th Advanced Automotive Battery Conference
San Francisco, CA
June 2-4, 2004

Matthew Zolot
Tony Markel
Ahmad Pesaran

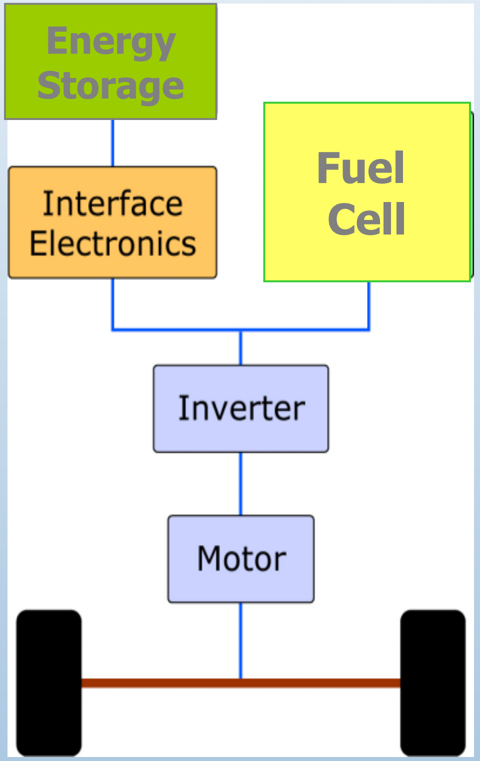
NREL is operated by Midwest Research Institute • Battelle

Content

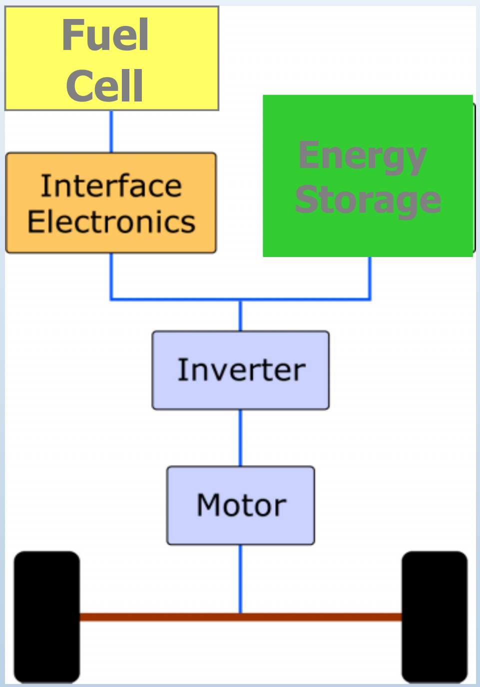
- Background
- Motivation/Objectives
- ADVISOR Vehicle Simulator
- Analyses
- Summary

Previous Studies

- **Hybridization of a fuel cell vehicle with energy storage improves fuel economy, performance and make it practical (UCD, VTech, ANL, NREL)**
  - Capturing regenerative breaking
  - Improving transient response
  - Smaller fuel cell - lower cost
  - Fuel cell or reformer warm up
- **Some demonstration prototype fuel cell vehicles are hybrids**
  - Toyota FCHV, Ford Focus– (batteries)
  - Honda FCXV4 – (ultracapacitors)



Motivation for this Study



- Previous studies have not separated the degree of hybridization benefits from:

  (a) fuel cell efficiency characteristics,
  (b) fuel cell downsizing,
  (c) displacing fuel cell tasks with the ES functionality
  (d) energy recovery through regenerative braking

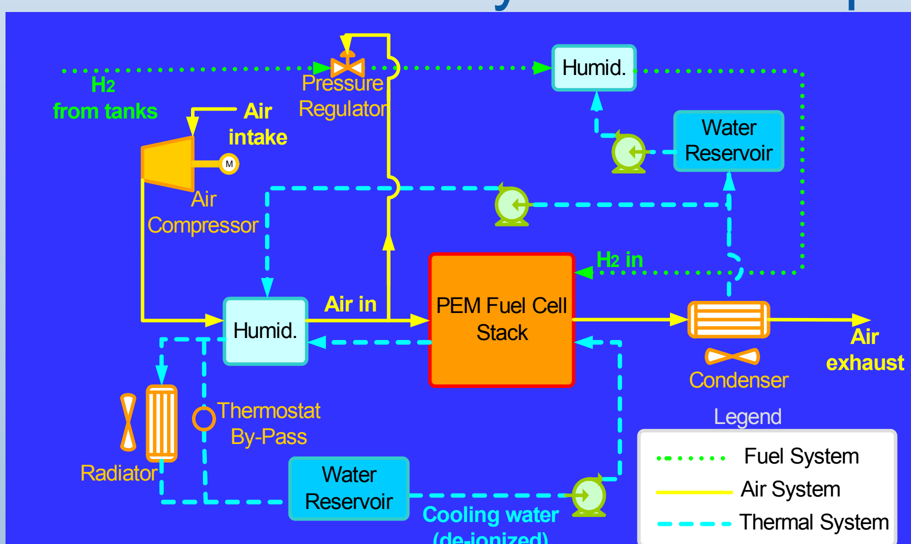
- Supporting FreedomCAR in identifying requirements of energy storage for hybrid fuel cell vehicles

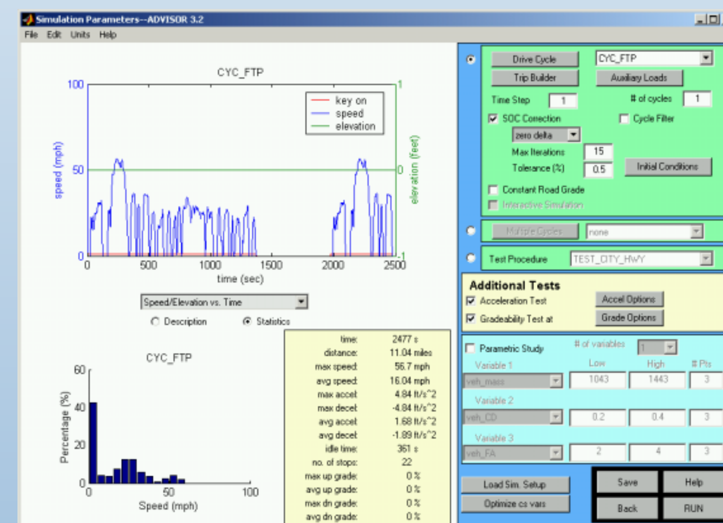
Objectives

- Investigate the degree of hybridization benefit from:
  (A) Fuel cell efficiency characteristics
  (B) Fuel cell downsizing
  (C) Displacing fuel cell tasks with the ES functionality
  (D) Energy recovery through regenerative braking

ADVISOR^{TM} Tool is Used for HFCV Simulations

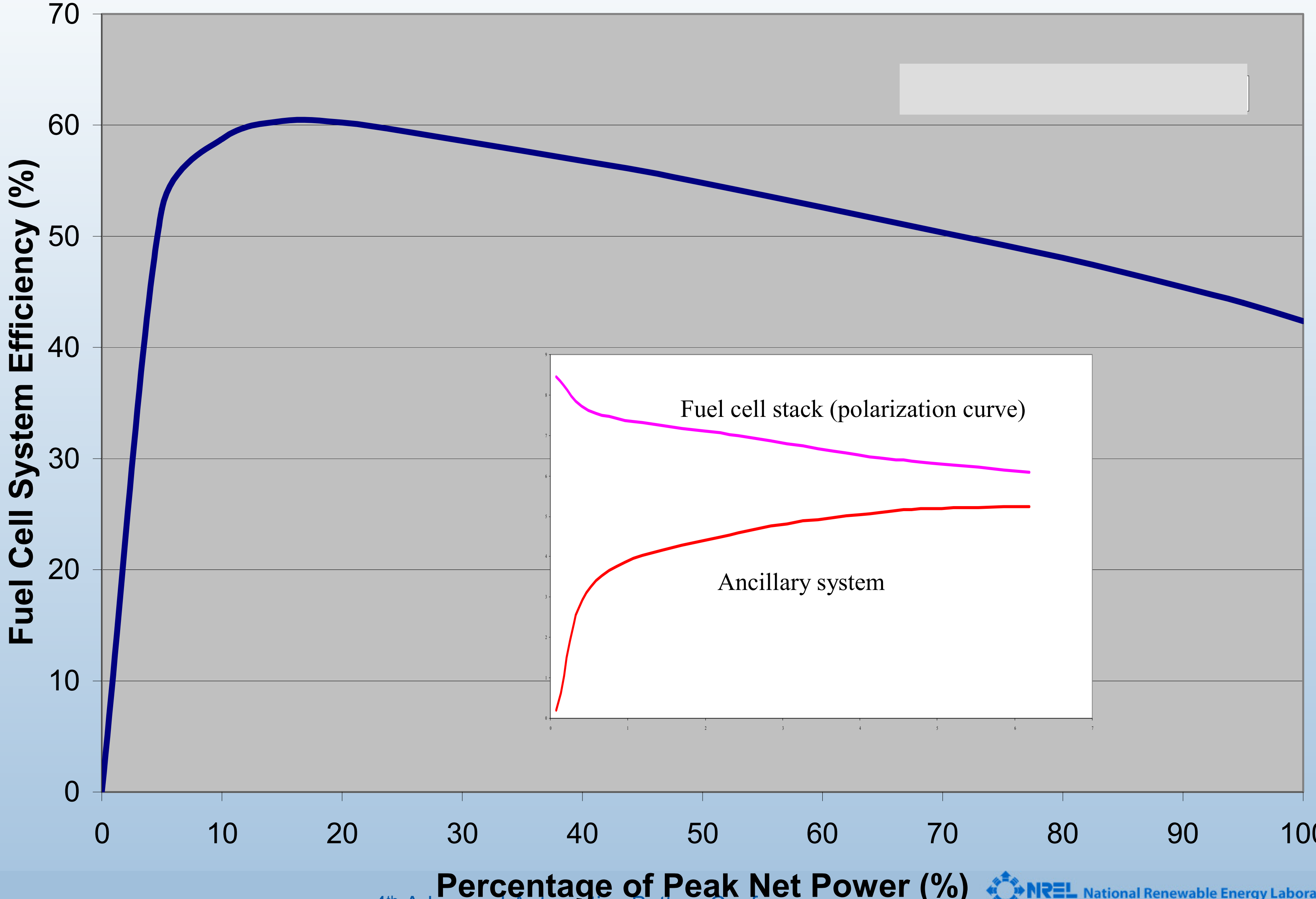
- ADVISOR^{TM} = ADvanced VehIcle SimulatOR
  - Simulates conventional, electric, or hybrid vehicles (series, parallel, or fuel cell)
  - Simulates various components (ES, FC) and drive cycles
- ADVISOR^{TM} was created in 1994 to support DOE Hybrid Program research decisions
- Available from www.nrel.gov/transportation/analysis
- Downloaded by over 8000 people around world



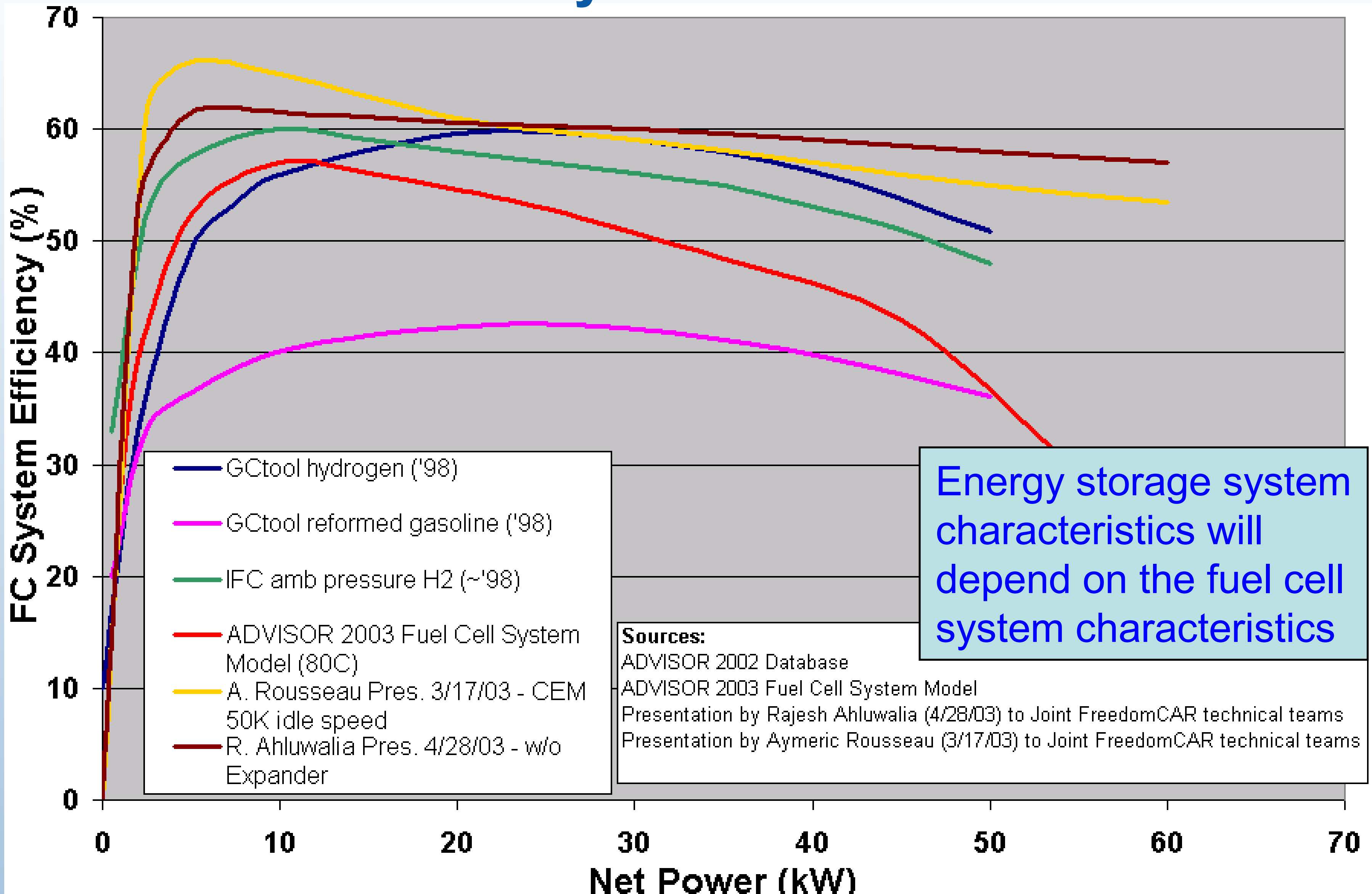


NREL National Renewable Energy Laboratory

Typical System Efficiency Characteristics from FC Model

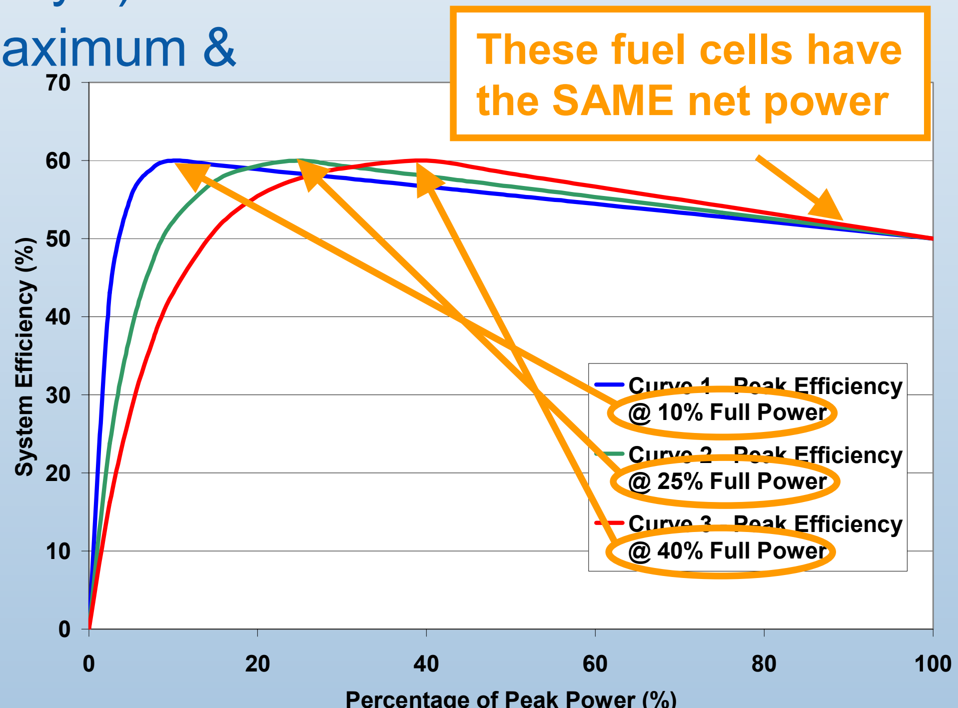


Fuel Cell System Efficiency Variability Could Affect FC-ES Hybridization Outcome



Fuel Cell and Hydrogen Storage System Assumptions

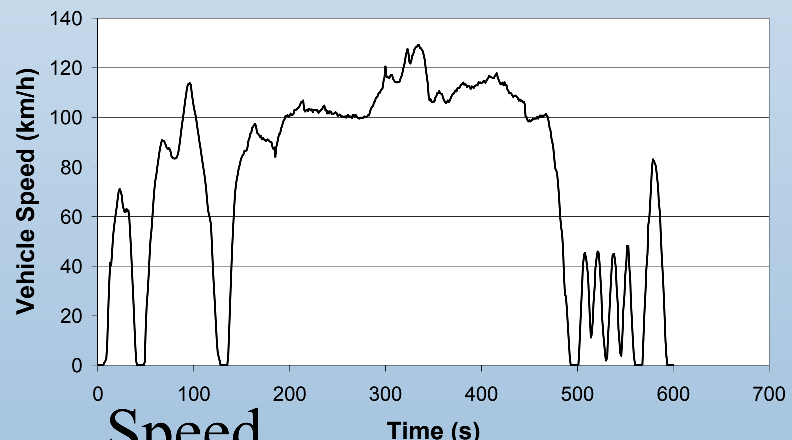
- Fuel Cell
  - Sized to provide at least grade performance.
  - 1 s or 3 s transient response time (10% to 90% power).
  - Reaches maximum rated power in 0 s (ideal case), 15 s (2010 target), or 60 s (today’s) for cold start from 20°C.
  - System efficiency of 60% at maximum & 50% at rated peak power (DOE Technical Targets) .
- Hydrogen Storage
  - Pure compressed hydrogen.



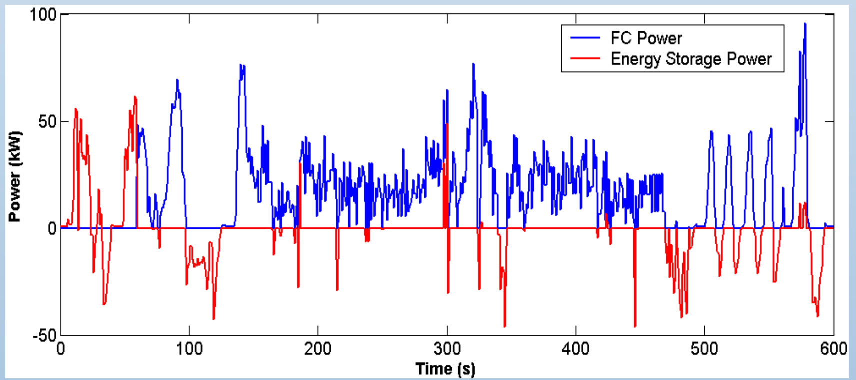
Proposed theoretical FC efficiency curves are based on DOE Targets

Objectives

- Investigate the degree of hybridization benefit from:
  (A) Fuel cell efficiency characteristics
  (B) Fuel cell downsizing
  (C) Displacing fuel cell tasks with the ES functionality
  (D) Energy recovery through regenerative braking



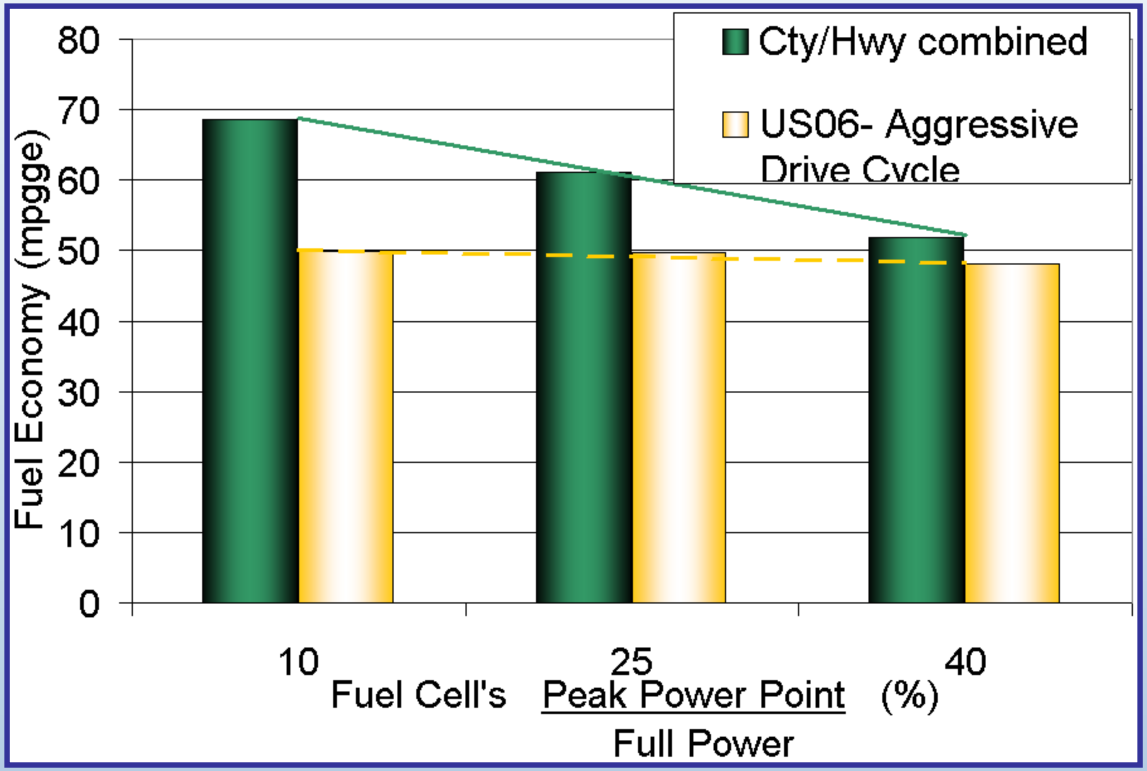
Speed



Power

Fuel Economy is Affected by the Position of FC Peak Efficiency

Vehicle with fuel cell only (96 kW)



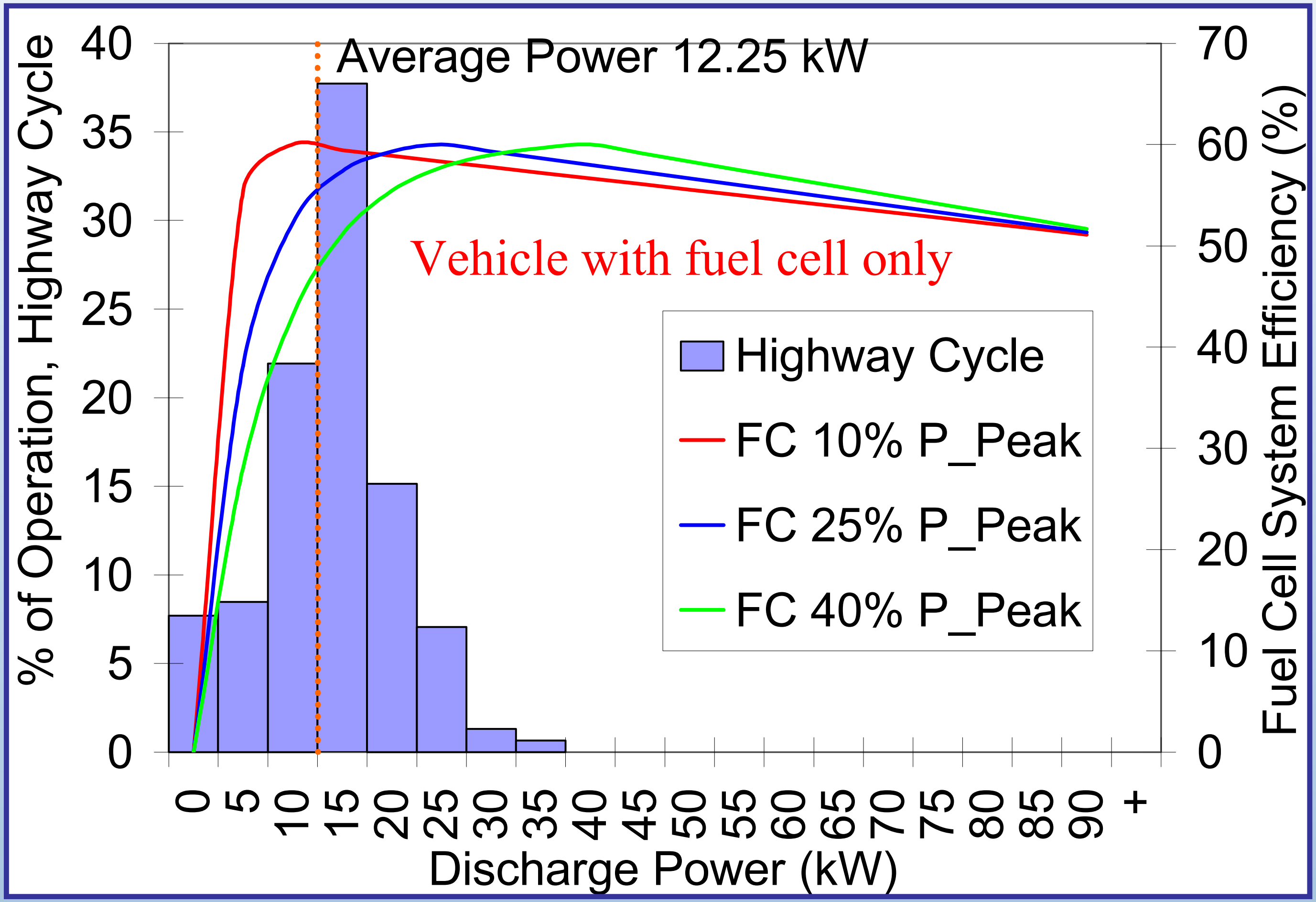
- 10% peak efficiency FC achieved the best city/highway fuel economy

  +12% improvement over the 25% peak efficiency configuration

  +32% improvement over the 40% peak efficiency configuration

When Peak Efficiency ≅ Typical Power Point, Results in the Best Fuel Economy

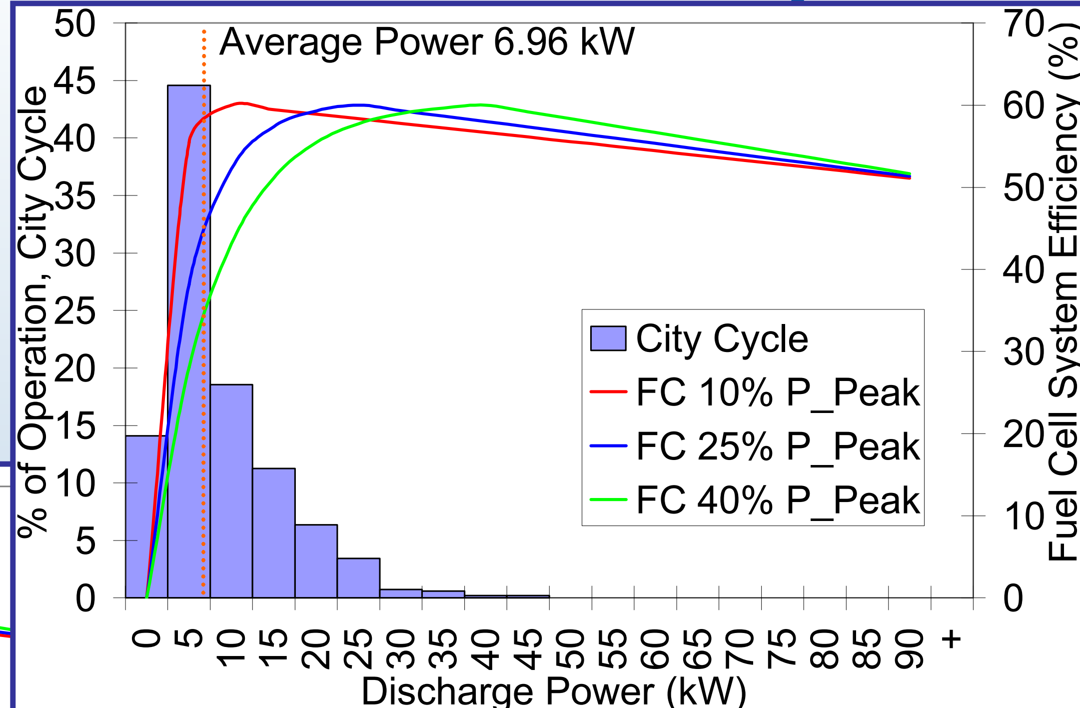
- 10% peak efficiency FC has the highest fuel economy because its peak efficiency is better aligned with the power requirements.

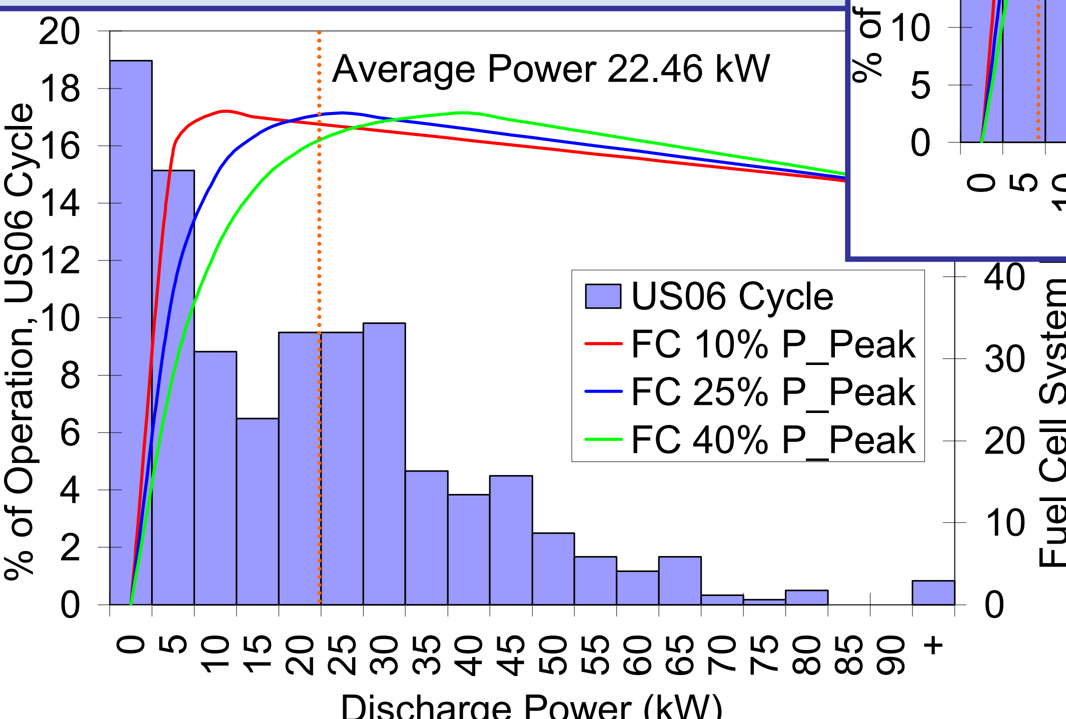


When Peak Efficiency ≅ Typical Power Point, Results in the Best Fuel Economy

- 10% peak efficiency FC has the higher fuel economy since its peak efficiency is matched better with City Drive Cycle power requirements.

Vehicle with fuel cell only





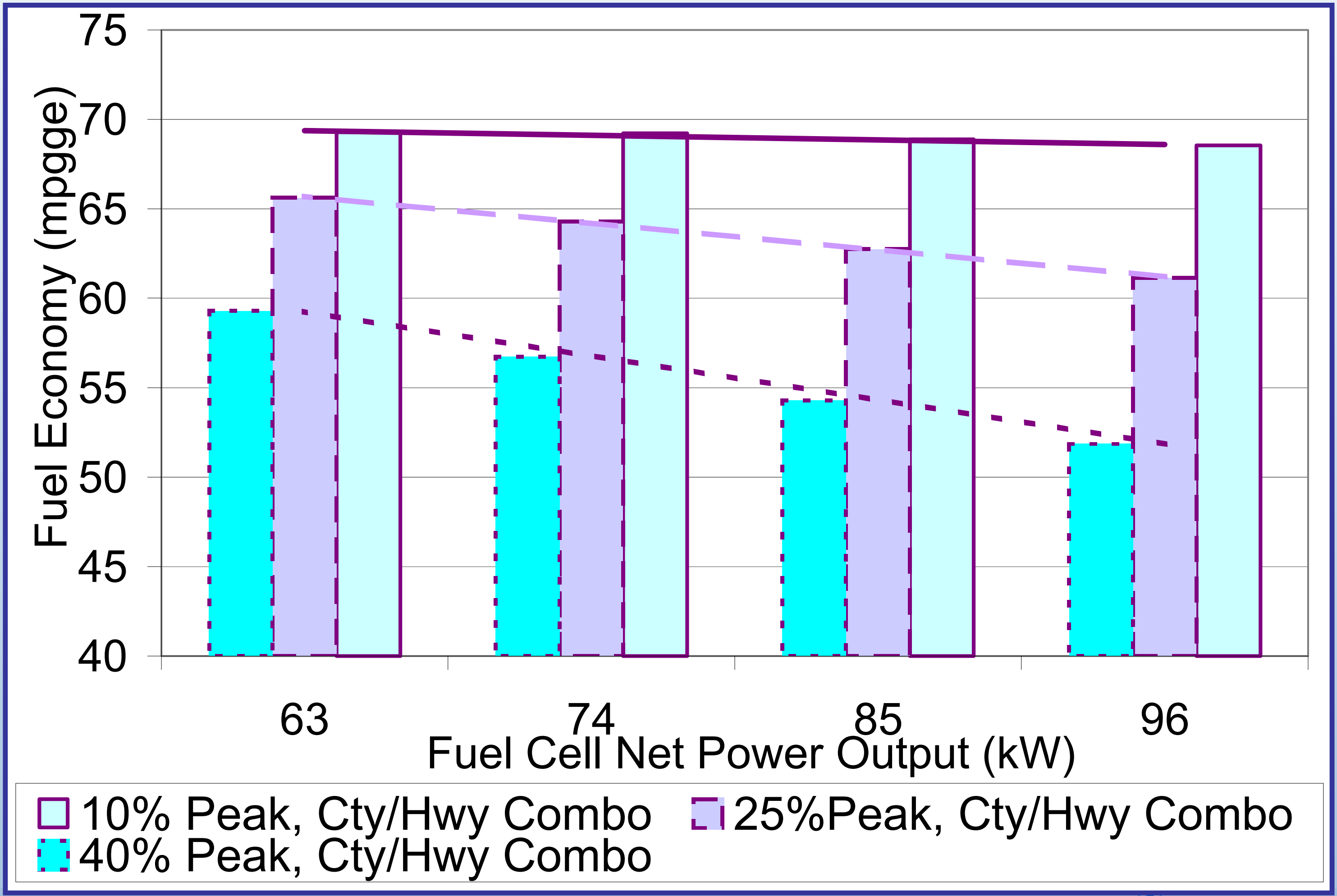
- Little fuel economy difference over US06 cycle.
  - wider power distribution
  - similar efficiency at P_{avg}

Objectives

- Investigate the degree of hybridization benefit from:
  (A) Fuel cell efficiency characteristics
  (B) Fuel cell downsizing
  (C) Displacing fuel cell tasks with the ES functionality
  (D) Energy recovery through regenerative braking

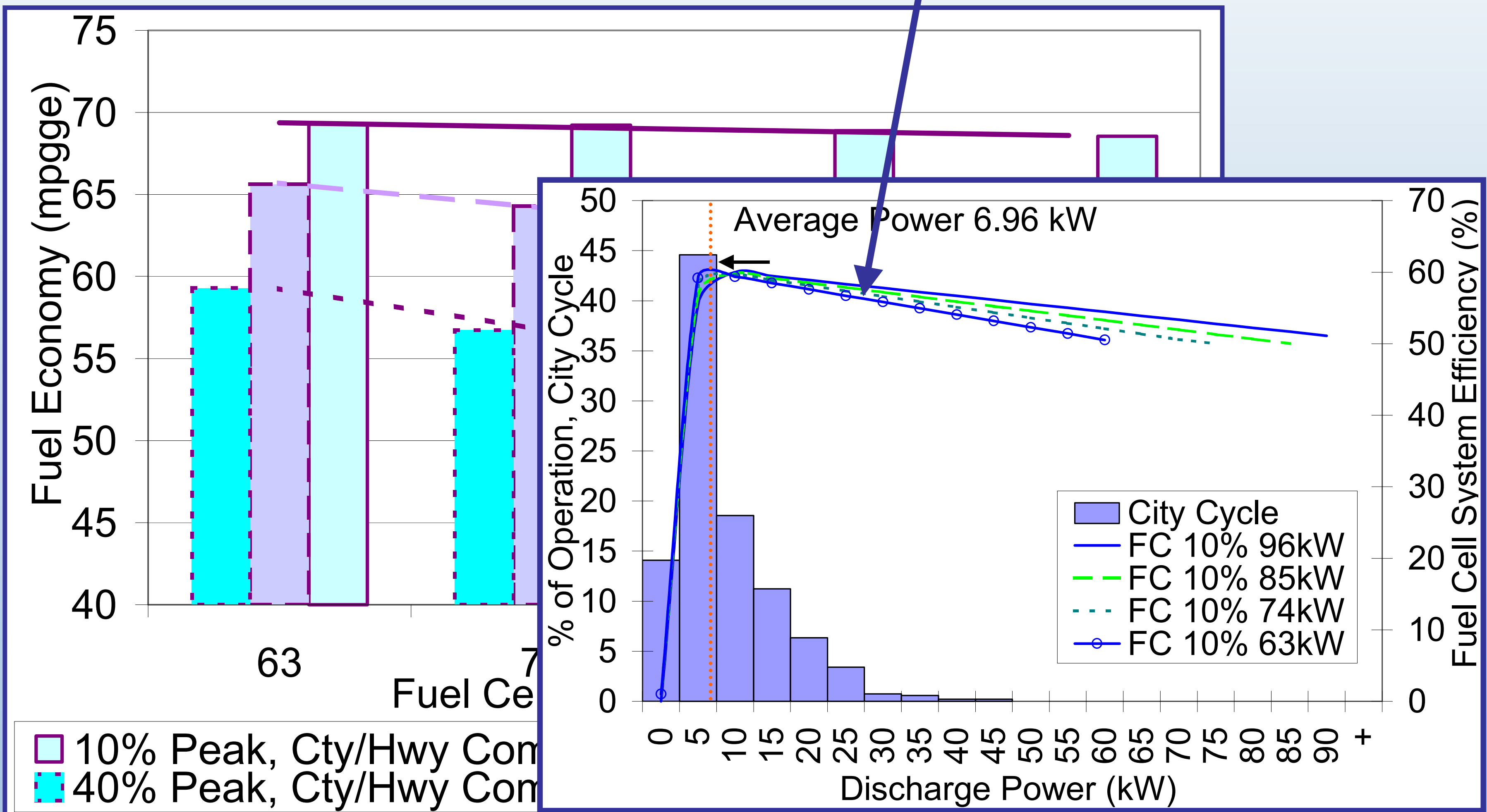
The Benefit of Downsizing the Fuel Cell varies as a function of Peak Efficiency Position

- Downsizing the 10% peak efficiency FC results in the least potential fuel economy improvement



The Benefit of Downsizing the Fuel Cell varies as a function of Peak Efficiency Position

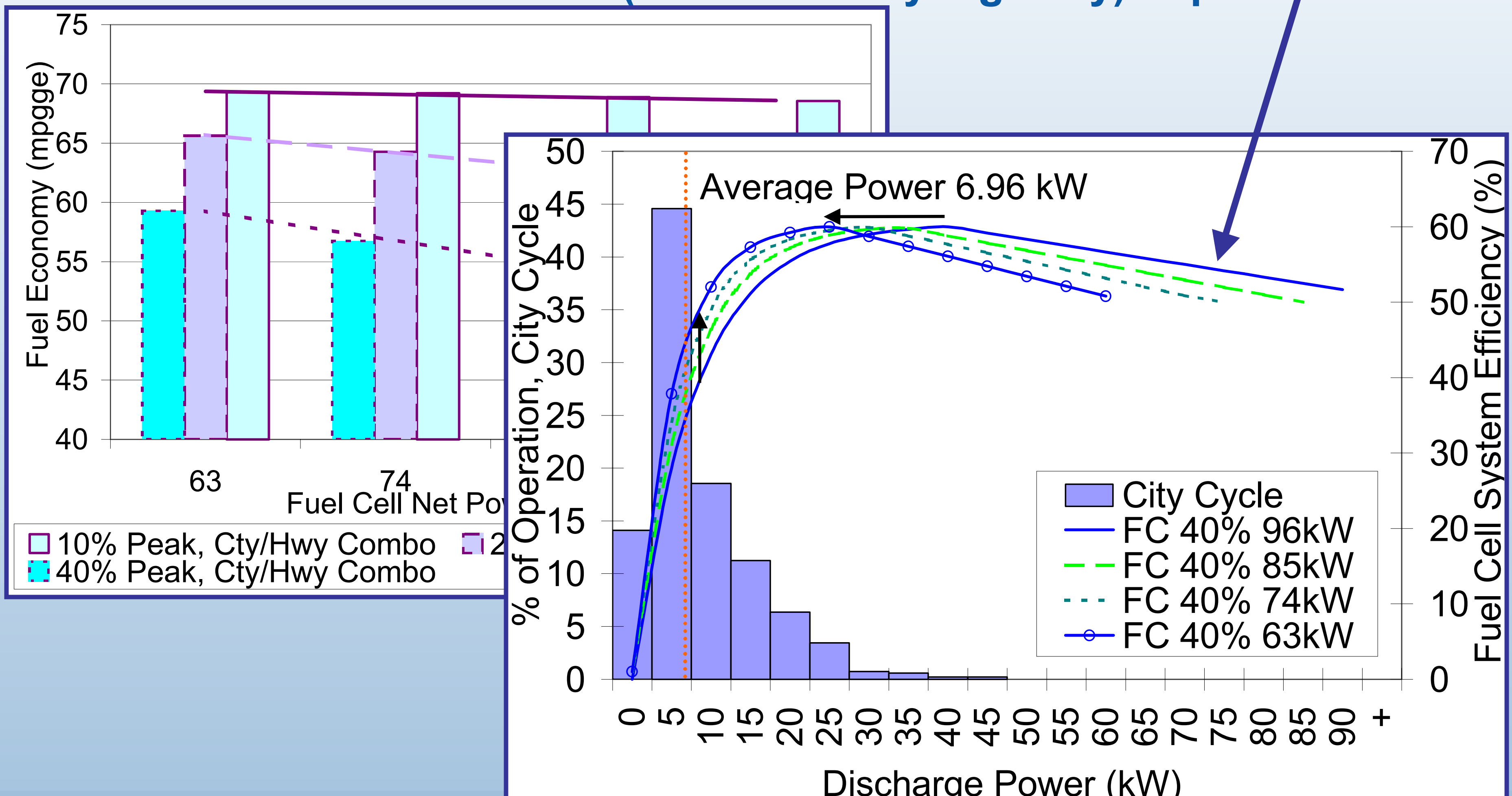
- Downsizing the 10% peak efficiency FC results in the least potential fuel economy improvement ≤ **1.0% (combined city/highway) improvement**



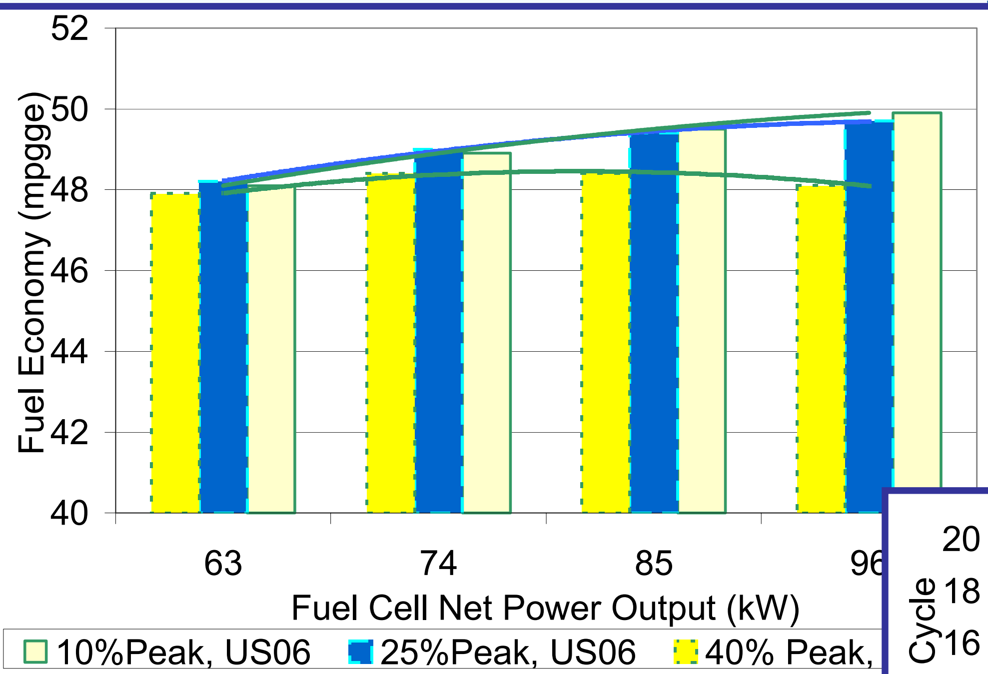
The Benefit of Downsizing the Fuel Cell varies as highest with a flat FC Efficiency Curve

- Downsizing the 40% peak efficiency FC results in a moderate to significant potential fuel economy improvement

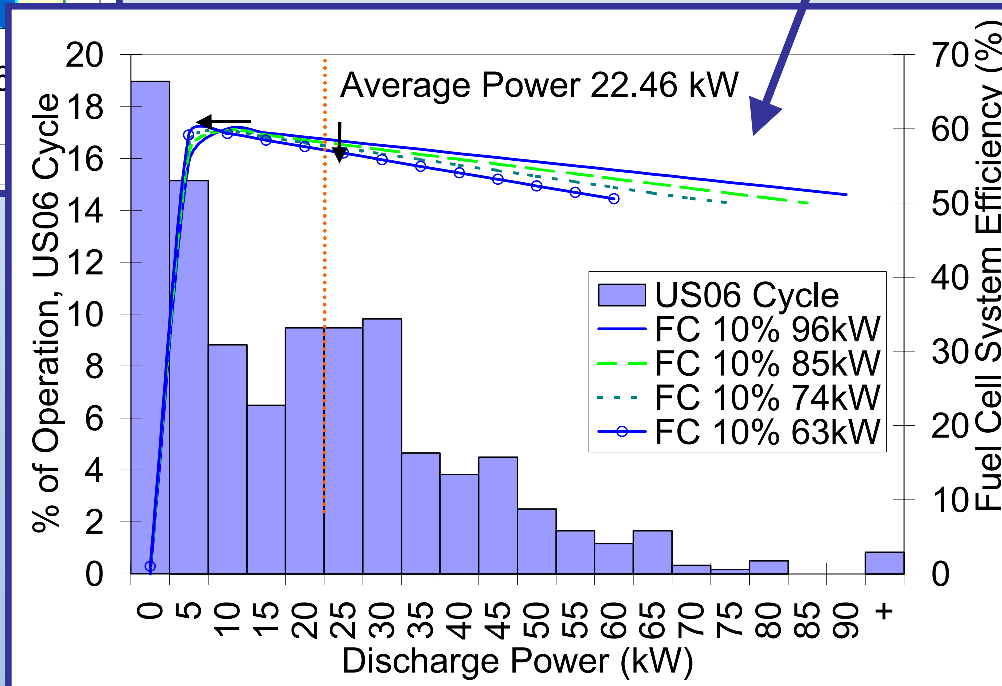
≤ 15.0% (combined city/highway) improvement



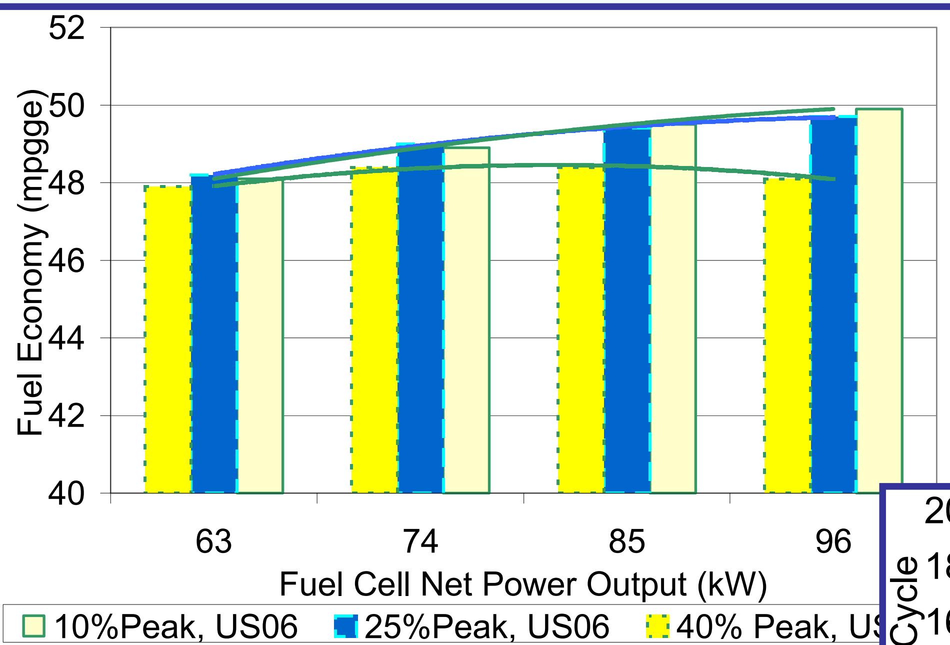
Downsizing the Fuel Cell Can Have a Negative Effect on the US06 Cycle Fuel Economy



- Downsizing the 10% & 25% peak efficiency FCs results in up to…
  2 mpg less fuel economy

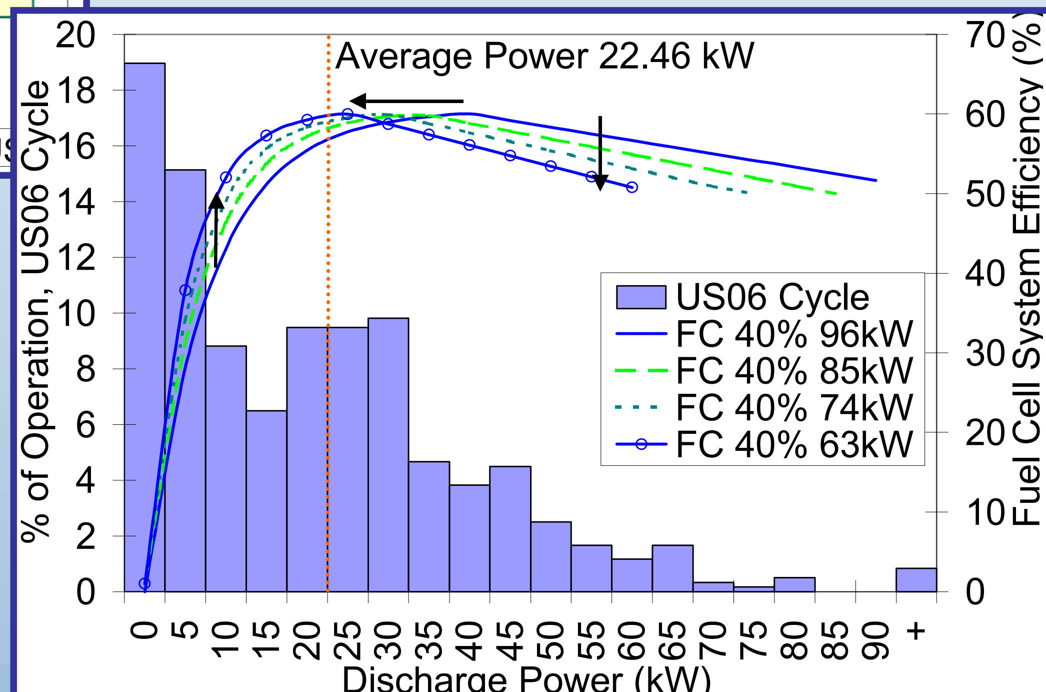


Downsizing the Fuel Cell Can Have a Negative Effect on the US06 Cycle Fuel Economy



- Downsizing the 40% peak efficiency FC results in…

  fairly even fuel economy



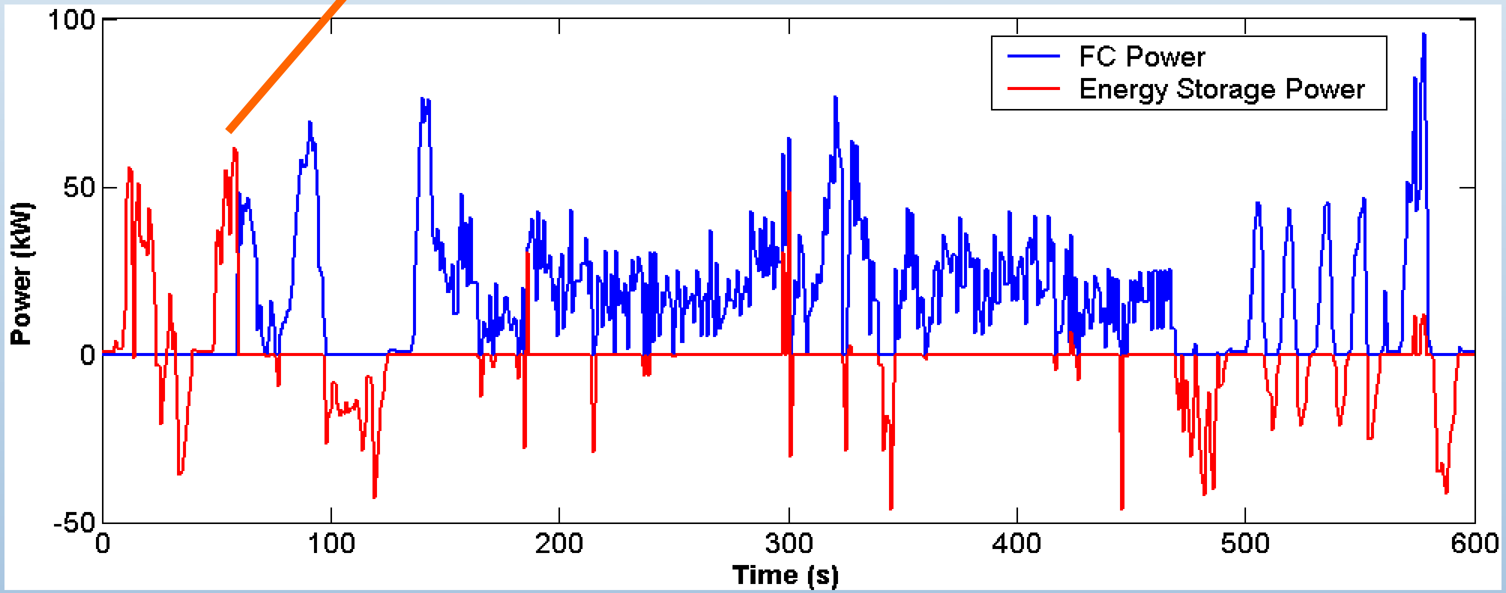
Objectives

- Investigate the degree of hybridization benefit from:
  (A) Fuel cell efficiency characteristics
  (B) Fuel cell downsizing
  (C) Displacing fuel cell tasks with the ES functionality
  (D) Energy recovery through regenerative braking

Energy Storage Requirements for Supplementing a Full-Size FC's Limitations

96 kW Fuel Cell	Warm-Up Time (s)	Ramp Rate 10-90% (s)	$P_{req'd}$ (kW)	$E_{req'd}$ (kWh)	P_{regen} (kW)	E_{regen} (kWh)
Today's Perfomance	60	3	61.80	0.2206	-46.49	-0.7332
	60	1	61.80	0.2206	-48.05	-0.7332
	15	3	55.90	0.0580	-46.49	-0.8237
2010 Target	15	1	55.90	0.0580	-48.05	-0.8237
	0	3	48.86	0.0067	-46.49	-0.8265
"Ideal" 96 kW Case	0	1	0.00	0.0000	-48.05	-0.8265

- Similar to stated Honda FCX4 ESS roles.
- Warm-up and ramp rate ESS roles require relatively little energy.

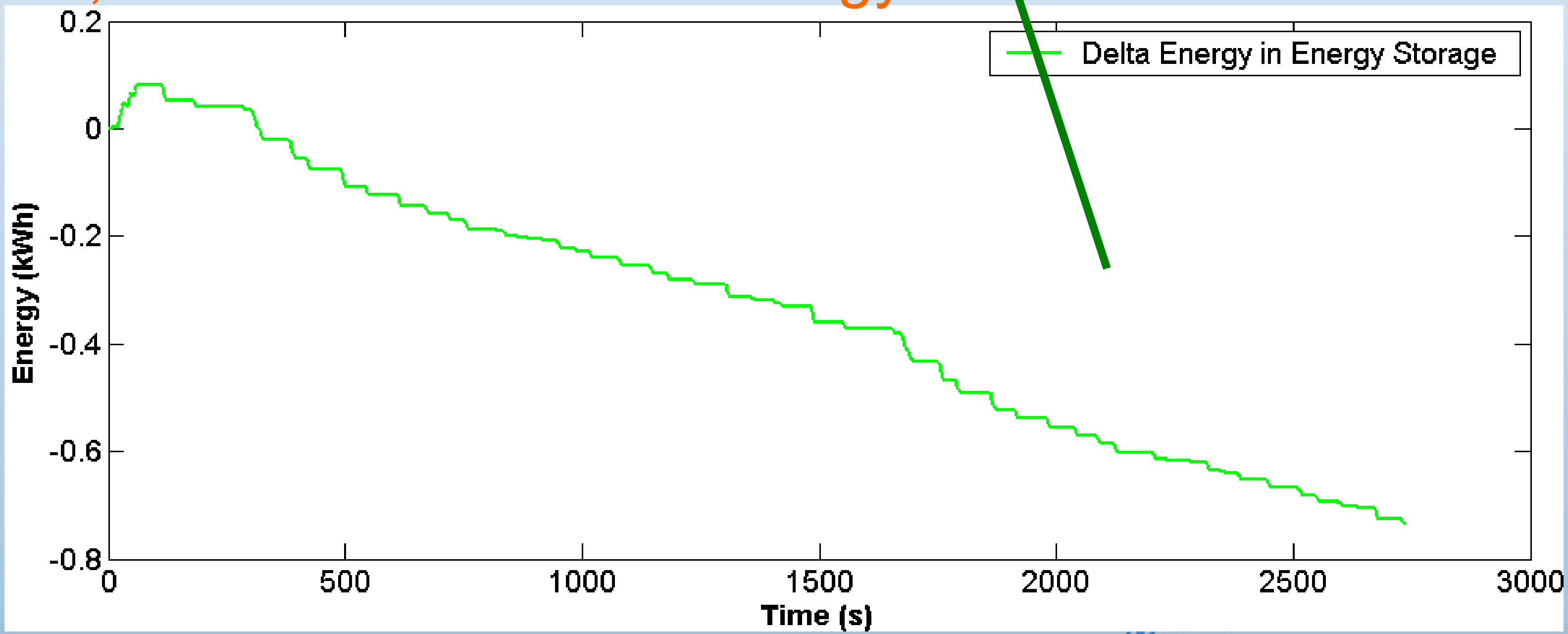


Energy Storage Requirements for Supplementing a Full-Size FC's Limitations

96 kW Fuel Cell	Warm-Up Time (s)	Ramp Rate 10-90% (s)	P req'd (kW)	E req'd (kWh)	P regen (kW)	E regen (kWh)
Today's Perfomance	60	3	61.80	0.2206	-46.49	-0.7332
	60	1	61.80	0.2206	-48.05	-0.7332
	15	3	55.90	0.0580	-46.49	-0.8237
2010 Target	15	1	55.90	0.0580	-48.05	-0.8237
	0	3	48.86	0.0067	-46.49	-0.8265
"Ideal" 96 kW Case	0	1	0.00	0.0000	-48.05	-0.8265

- Big potential if more active ESS is used.

- 2010 Target performance needs fairly similar power, but much less assist energy.



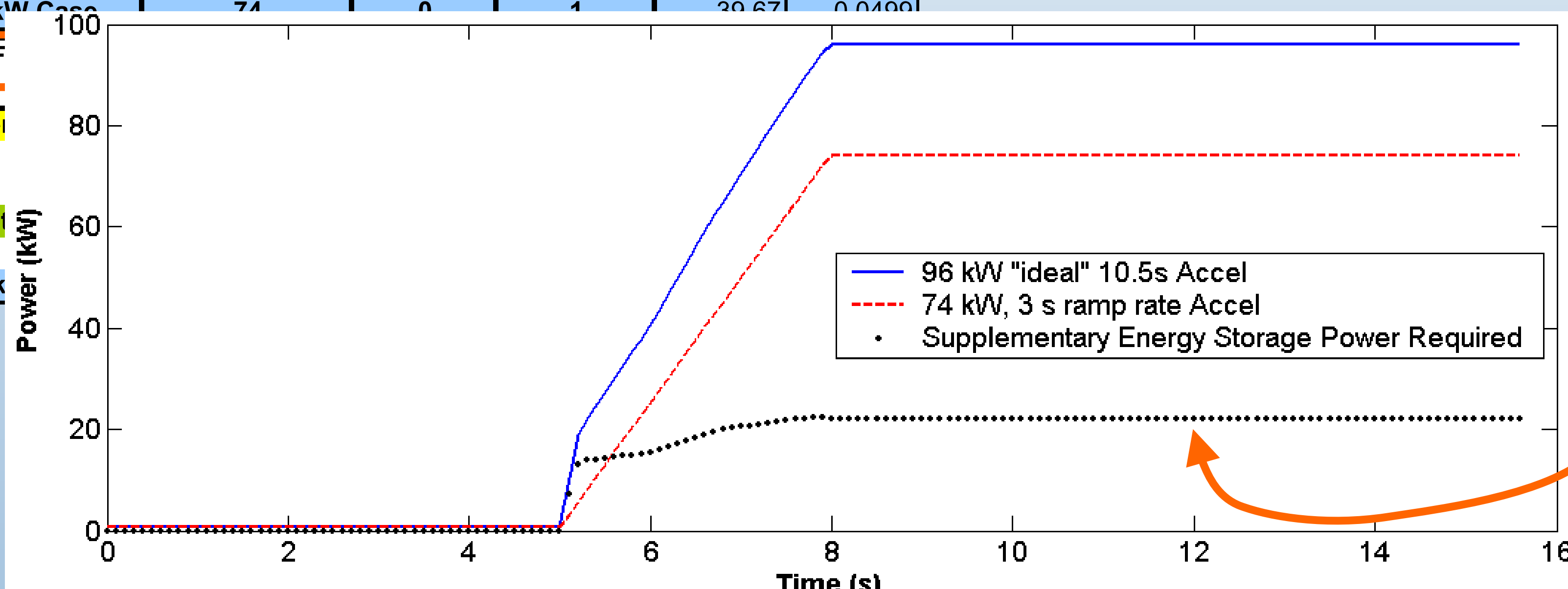
Energy Storage Requirements for Supplementing a Downsized FC's Limitations

85 kW Fuel Cell	Peak Shaving FC Power (kW)	Warm-Up Time (s)	Ramp Rate 10-90% (s)	$P_{req'd}$ (kW)	$E_{req'd}$ (kWh)
Today's Perfomance	85	60	3	61.80	0.2206
	85	60	1	61.80	0.2206
	85	15	3	55.90	0.0580
2010 Target	85	15	1	55.90	0.0580
	85	0	3	52.53	0.0333
"Ideal" 85 kW Case	85	0	1	28.67	0.0243

74 kW Fuel Cell	Peak Shaving FC Power (kW)	Warm-Up Time (s)	Ramp Rate 10-90% (s)	$P_{req'd}$ (kW)	$E_{req'd}$ (kWh)
Today's Perfomance	74	60	3	61.80	0.2206
	74	60	1	61.80	0.2206
	74	15	3	56.20	0.0611
2010 Target	74	15	1	55.90	0.0580
	74	0	3	56.20	0.0611
"Ideal" 74 kW Case	74	0	1	39.67	0.0499

63 kW F
Today's Pe
2010 Target
"Ideal" 63 k

- With FC downsized, ESS must also assist during max acceleration event.



Energy Storage Requirements for Supplementing a Downsized FC's Limitations

85 kW Fuel Cell	Peak Shaving FC Power (kW)	Warm-Up Time (s)	Ramp Rate 10-90% (s)	P req'd (kW)	E req'd (kWh)
Today's Perfomance	85	60	3	61.80	0.2206
	85	60	1	61.80	0.2206
	85	15	3	55.90	0.0580
2010 Target	85	15	1	55.90	0.0580
	85	0	3	52.53	0.0333
"Ideal" 85 kW Case	85	0	1	28.67	0.0243

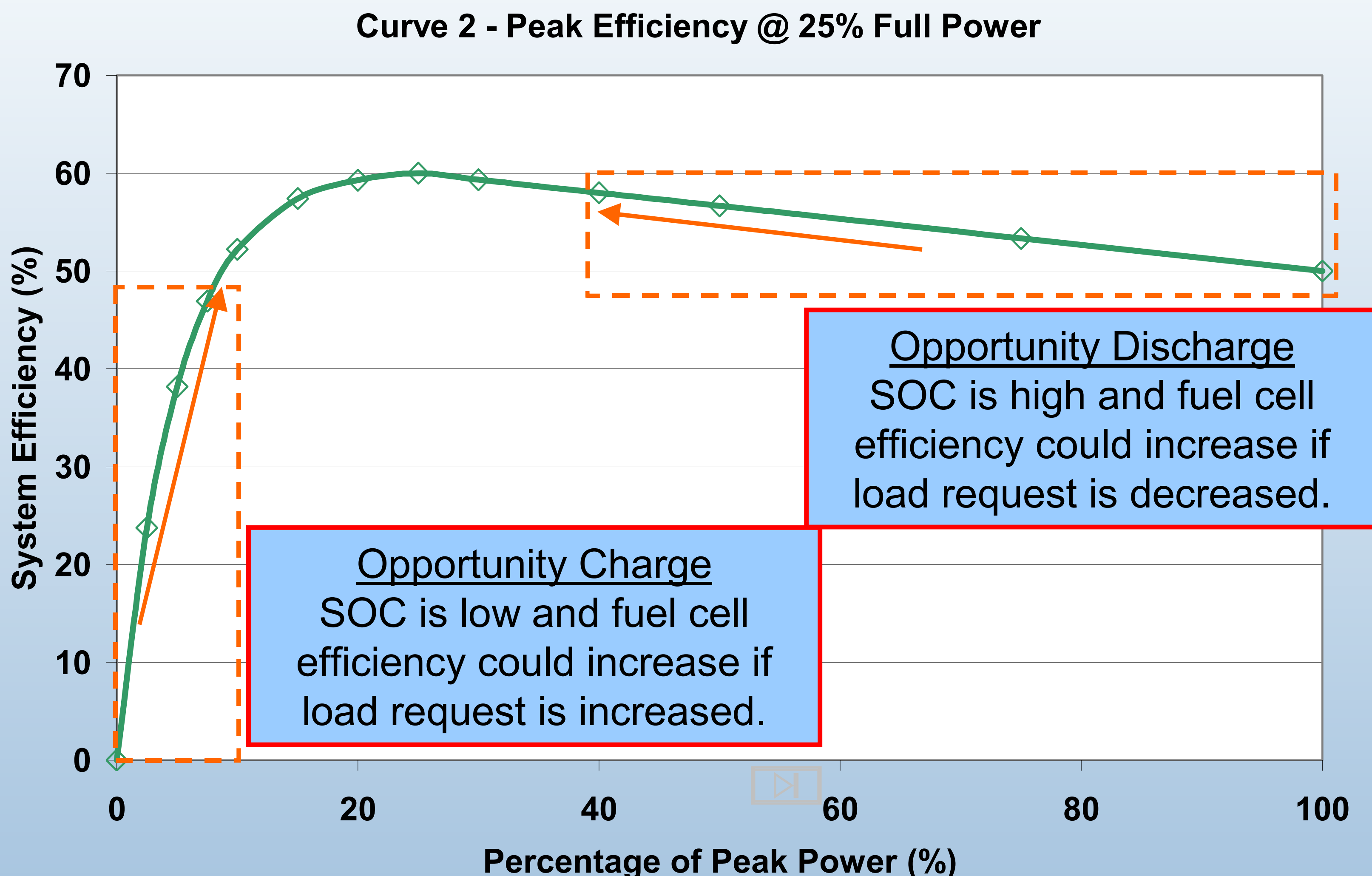
74 kW Fuel Cell	Peak Shaving FC Power (kW)	Warm-Up Time (s)	Ramp Rate 10-90% (s)	P req'd (kW)	E req'd (kWh)
Today's Perfomance	74	60	3	61.80	0.2206
	74	60	1	61.80	0.2206
	74	15	3	56.20	0.0611
2010 Target	74	15	1	55.90	0.0580
	74	0	3	56.20	0.0611
"Ideal" 74 kW Case	74	0	1	39.67	0.0499

63 kW Fuel Cell	Peak Shaving FC Power (kW)	Warm-Up Time (s)	Ramp Rate 10-90% (s)	P req'd (kW)	E req'd (kWh)
Today's Perfomance	63	60	3	61.80	0.2206
	63	60	1	61.80	0.2206
	63	15	3	59.90	0.0889
2010 Target	63	15	1	55.90	0.0766
	63	0	3	59.90	0.0889
"Ideal" 63 kW Case	63	0	1	50.70	0.0766

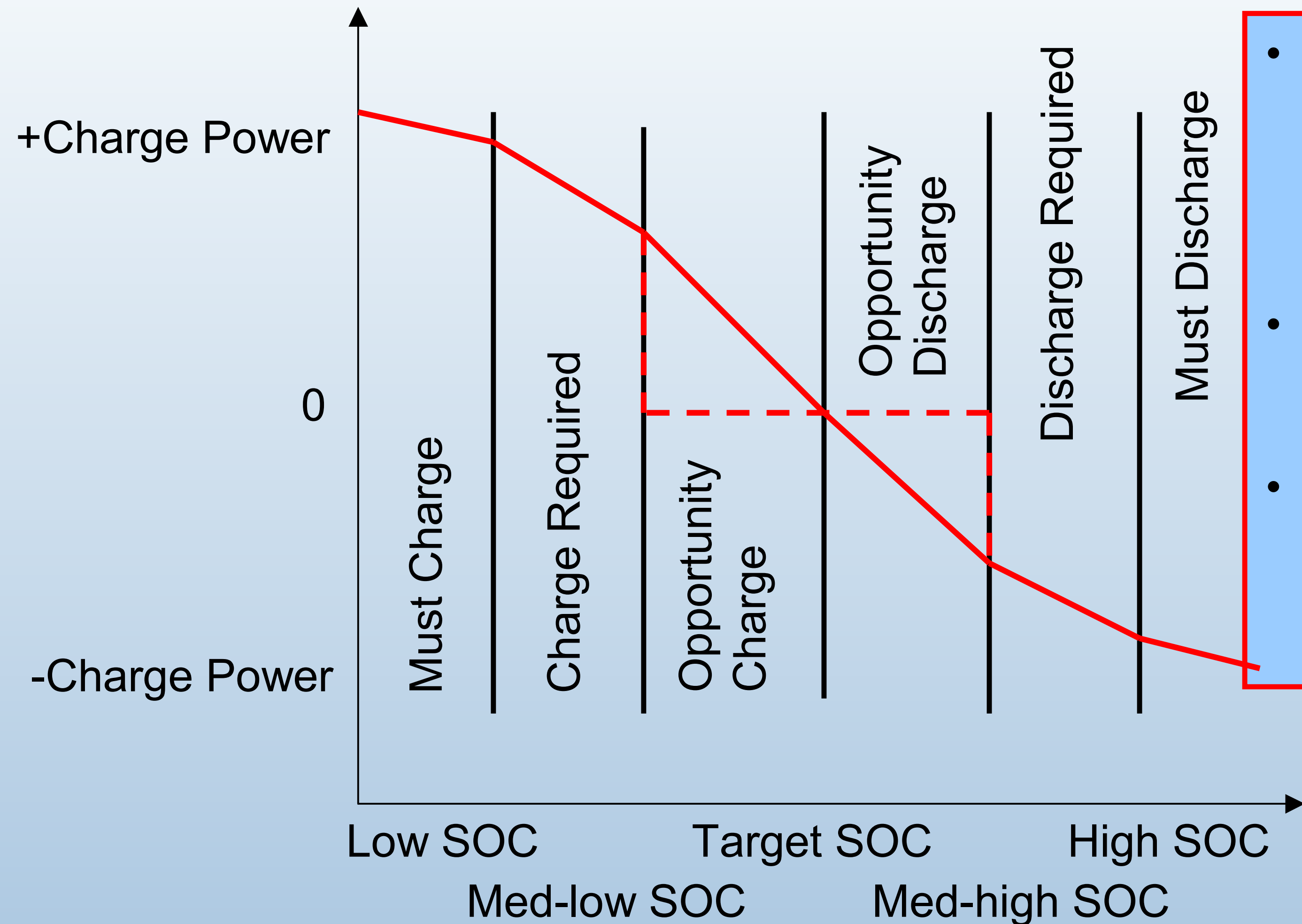
- With FC downsized, ESS must also assist during max acceleration event.
- ESS is the same as a full-sized FC requires for "Today's" fuel cell performance.
- ESS is nearly the same as a full-sized FC requires for "2010 Target" fuel cell performance.

- Therefore, downsizing provides improvement in fuel economy, fuel cell costs, and [in minimal control case] has little to no affect on ESS sizing.

Current Work - Potential Active Roles for Supplementing Fuel Cell Operation



Current Work - Multi-region "Spring" SOC Maintenance Algorithm



- Opportunity region
  - only take action if it makes the prime power plant more efficient
- Could assume different charging rates in each region
- Number of parameters makes it harder to optimize and understand impacts

Fc_pwr_r = dl_pwr_r + charge_pwr

Summary

- The best fuel economy occurs when peak FC efficiency ≅ typical power operating point (cycle dependant).
- There is positive benefit of downsizing the FC if the peak efficiency is shifted toward the typical power operating point (cycle dependant).
- ES requirements for supplementing FC limitations are suitable for Ultracapacitors or High Power Batteries.
- Downsizing a FC (toward the gradeability limit) with today's or 2010 projected characteristics, does NOT significantly affect ES requirements (with minimal ES control case).
- There is significant potential for more actively using the ES to manage the FC operation points because of un-used regenerative energy capture.

Acknowledgements

- Sponsored by U.S. Department of Energy's Office of FreedomCAR and Vehicle Technologies.
- Appreciate the support and technical guidance from USABC/FreedomCAR ES Technical Team

www.ctts.nrel.gov/BTM
www.ctts.nrel.gov/analysis